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Improvements in Techniques of Microwave Thermography

Annual Summary Report

15 November 1983 - 15 November 1984

Alan H. Barrett

June 11, 1985

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20. ABSTRACT

During the period 15 November 1983 to 15 November 1984 our efforts have focussed on (1) modifying our 3 and 6 GHz radiometers for reflection compensation and making design changes to improve the stability, (2) designing antennas to give improved penetration depth, and (3) bistatic measurements whereby the scattered radiation from an embedded object is determined to provide information on the size of the object and the proper frequency for hyperthermia. Measurements have shown that use of large-aperture antennas provide better penetration depth in human tissue. The bistatic experiments are directed toward utilizing the resonances which occur in the back scattered radiation as a function of the size of the scatterer and the wavelength of the radiation to establish the size of the scatterer and the optimum frequency at which maximum absorption will occur.

SUMMARY

During the period 15 November 1983 to 15 November 1984 our efforts have focussed on (1) modifying our 3 and 6 GHz radiometers for reflection compensation and making design changes to improve the stability, (2) designing antennas to give improved penetration depth, and (3) bistatic measurements whereby the scattered radiation from an embedded object is determined to provide information on the size of the object and the proper frequency for hyperthermia. Measurements have shown that use of large-aperture antennas provide better penetration depth in human tissue. The bistatic experiments are directed toward utilizing the resonances which occur in the back scattered radiation as a function of the size of the scatterer and the wavelength of the radiation to establish the size of the scatterer and the optimum frequency at which maximum absorption will occur.

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BODY OF THE REPORT

During the period 15 November 1983 to 15 November 1984 our research and development has concentrated in three areas: (1) modifying our standard Dicke radiometers at 3 and 6 GHz to reflection-compensating radiometers similar to our 1.4 GHz radiometer and making design changes to improve the overall stability of all three systems, (2) the design, construction, and evaluation of contact antennas, both dielectric-loaded and air-filled, for microwave thermography since the use of a reflection-compensating radiometer removes the need for a critical impedence match between the antenna and the tissue interface, and (3) bistatic measurements whereby a scattering object is illuminated by a source of incoherent microwave noise power and the reflected power is detected by a radiometer. The results of this research is summarized below.

Modification of Reflection-Compensating Radiometers

During the period of this Report our standard Dicke radiometers, operating at 3 and 6 GHz, have been modified to conform to the design of our 1.4 GHz reflection-compensating radiometers. The design of these radiometers was discussed in Annual Report No. 1.

A minor modification has been made to the radiometers which has been helpful in improving the overall repeatability of the radiometers. The microprocessor computes the reflection coefficient and the microwave temperature incident on the antenna. The physical temperature of the circulator enters into this computation and it had been our practice to use a nominal value for this temperature for all times. However, when looking at various heated dummy loads, either matched or mismatched, at an elevated temperature, the radiometer consistently computed a temperature differing from the true temperature by 1-2 C. This difference varied slowly during the day and is believed to have resulted from temperature changes of the circulator, due to variations in the ambient temperature and heating of the circulator by other components of the radiometer. We now have incorporated a temperature sensor on the circulator so that its temperature is read during each observation and used in each calculation of the reflection coefficient and microwave temperature. This has resulted in a significant reduction in the drift of the radiometer with time.

The ability of a reflection-compensating radiometer to correct for the effects of an impedance mismatch at the antenna-tissue interface is shown in Figure 1. For a multi-purpose radiometer used for microwave thermography, reflection compensation is vital because of the varying dielectric properties of tissue, fat, and muscle in different parts of the body.

Evaluation of Contact Antennas

Utilization of a reflection-compensating radiometer for microwave thermography has an important implication for the design of antennas used in thermography. In the past, antennas have been designed using dielectric-filled waveguides with the dielectric constant chosen to provide a good match to body tissue. Typical dielectric constants have been about 5. This has permitted propagation in waveguides $\sqrt{5}$ times smaller in linear dimensions than would otherwise be possible for the same frequency. With the advent of reflection-compensating radiometers, however, the need for good impedance match at the antenna-tissue interface is alleviated, to a large degree. This is because the radiometer corrects for the mismatch by computing the reflection

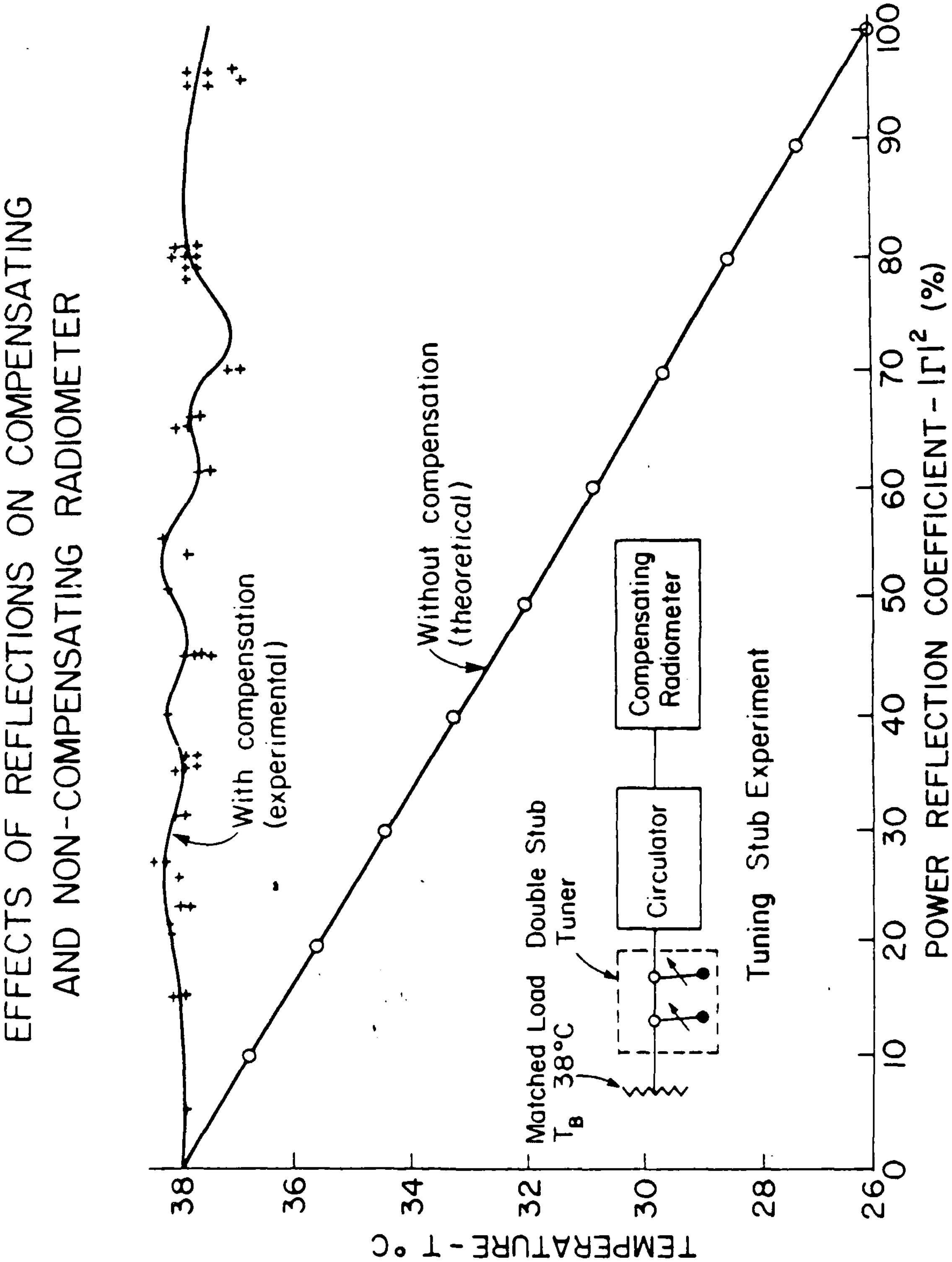
EFFECTS OF REFLECTIONS ON COMPENSATING AND NON-COMPENSATING RADIOMETER
With compensation (experimental)
Without compensation (theoretical)
Matched Load T_B 38°C
Double Stub Tuner
Circulator
Compensating Radiometer
Tuning Stub Experiment
TEMPERATURE - T °C
POWER REFLECTION COEFFICIENT - $|\Gamma|^2$ (%)
38
36
34
32
30
28
26
0
10
20
30
40
50
60
70
80
90
100

Figure 1

coefficient and using it in the computation of the microwave temperature. This has made the design and fabrication of the antennas considerably simpler, and therefore, cheaper. Furthermore, it has allowed one to use rather large, air-filled antennas without the complication of higher-order waveguide modes, as would occur with the same size antenna filled with a dielectric. The importance of being able to use larger air-filled waveguides is that the aperture size, measured in terms of wavelengths in tissue, approaches or exceeds one wavelength and leads to improved penetration depth. It should be pointed out that the use of large-aperture antennas leads to a loss of angular resolution, but this should not be detrimental when the antennas are used in a correlation interferometer because the angular resolution is determined to a large degree by the linear separation of the antennas. Under these circumstances the antennas should be optimized for depth penetration at the expense of lateral resolution.

The above results have been borne out by experimental measurements using a Zener diode noise source, slabs of dielectric material which stimulate tissue, and our reflection-compensating radiometer at 3 GHz. The Zener diode noise source is powered by a DC voltage through short resistive leads to reduce scattering from the leads. It is a convenient noise source, although uncalibrated as a thermal source, stable and easily variable by adjusting the DC voltage. For relative measurements, such as antenna power patterns or penetration depth measurements, it has been very satisfactory. The experimental set-up for our near-field measurements is shown in Figure 2 and some results for various antennas are shown in Figure 3. The dielectric constants of the material in the waveguide antennas A, B, and C is 1.0, 4.0, and 8.0, respectively. Note, antenna A is an air-filled antenna.

NEAR FIELD MEASUREMENTS OF HORN PATTERNS IN BREAST MATERIAL

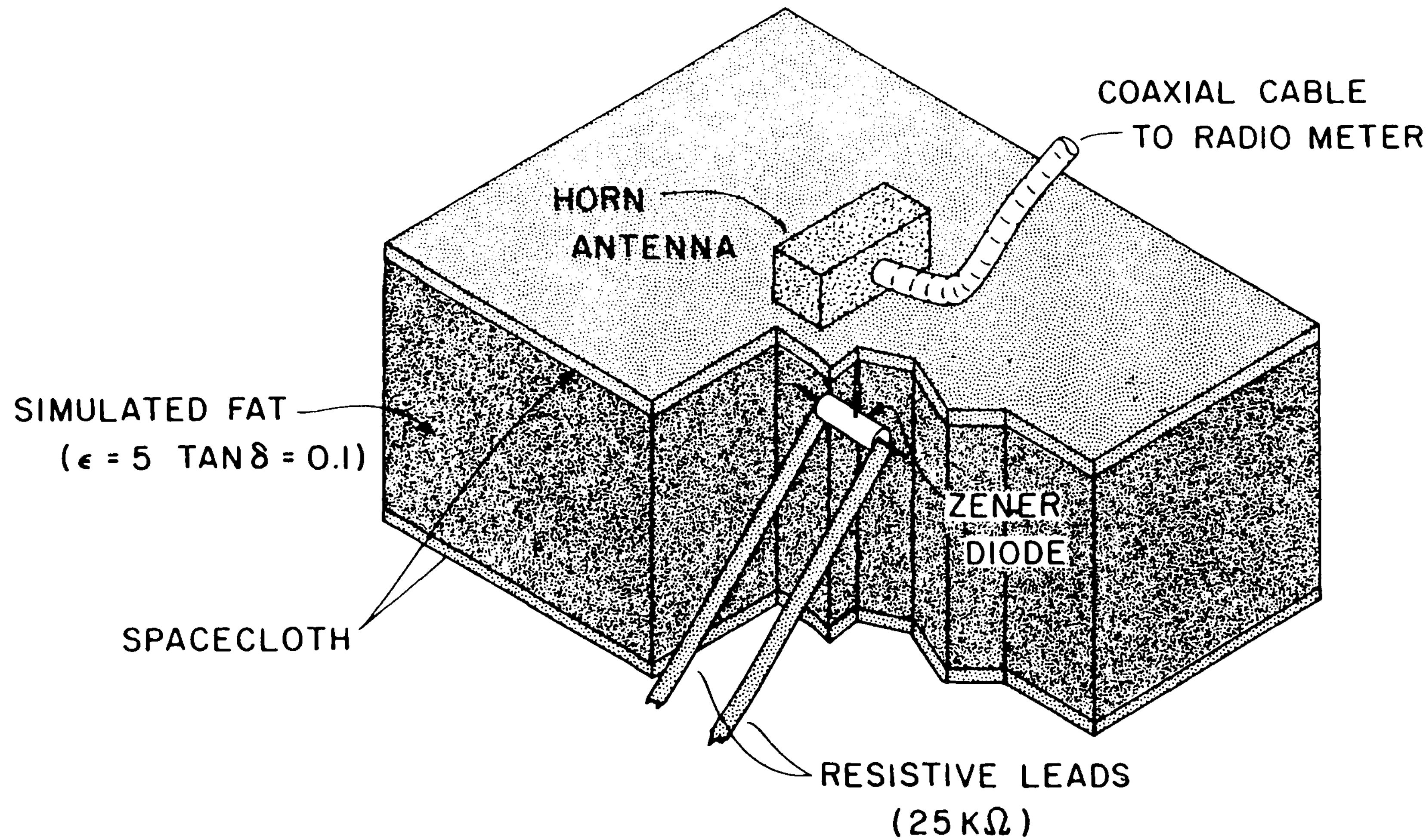

Figure 2

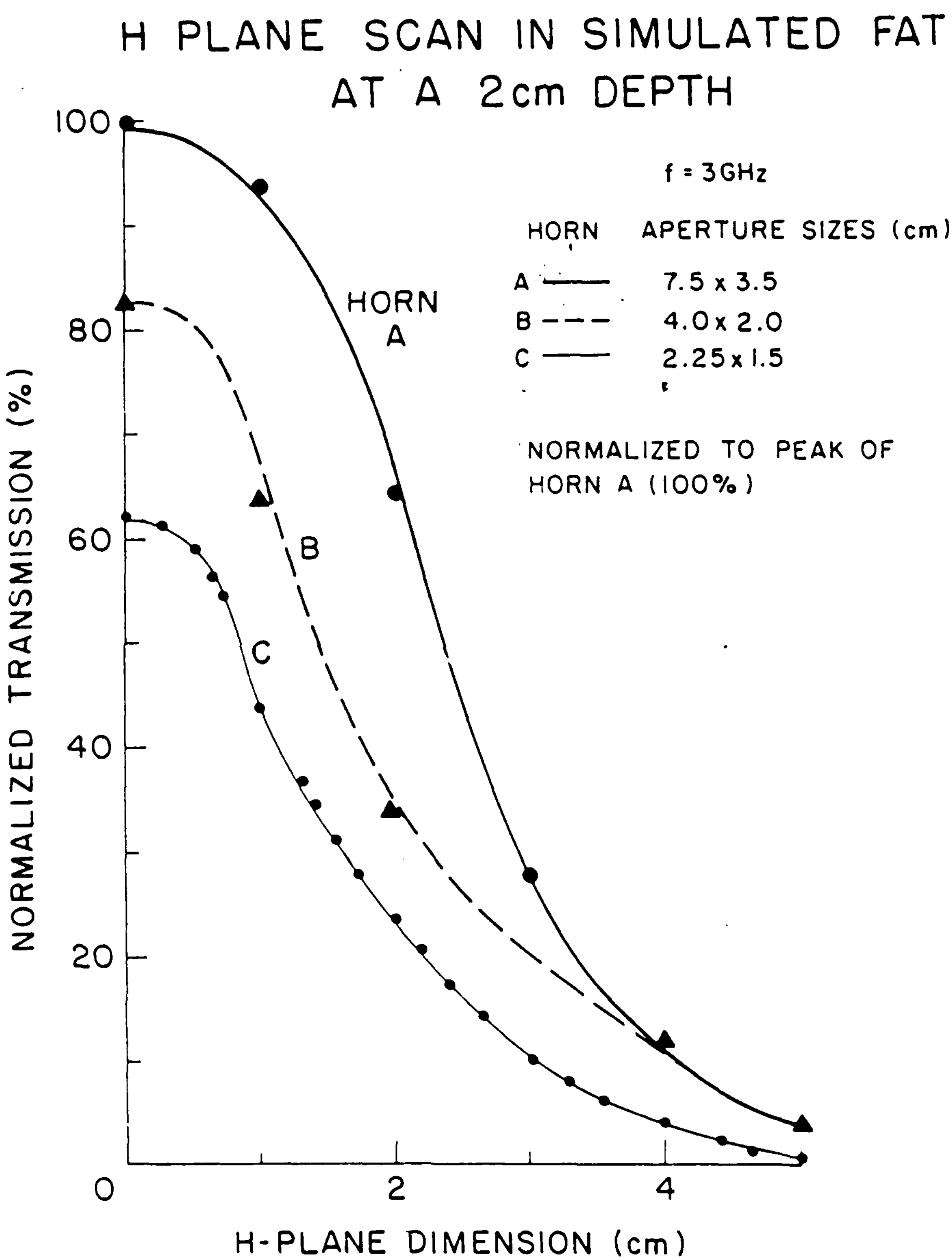
H PLANE SCAN IN SIMULATED FAT
AT A 2cm DEPTH
f = 3GHz
HORN APERTURE SIZES (cm)
A 7.5 x 3.5
B 4.0 x 2.0
C 2.25 x 1.5
NORMALIZED TO PEAK OF
HORN A (100%)
HORN
A
B
C
NORMALIZED TRANSMISSION (%)
100
80
60
40
20
0
2
4
H-PLANE DIMENSION (cm)

Figure 3

Bistatic Measurements

The potential application of interferometric techniques to microwave thermography is of interest because it will significantly improve the angular resolution and could provide medical personnel with a thermal image of the area surveyed. Several papers have been published recently on the feasability of interferometry applied to microwave thermography. These include those by Mamoui, et al. [Jour. of Microwave Power, 18 (3), 285 (1983)], Bellarbi, et al. [Electronics Letters, 20, 431 (1984)] , Hill and Goldner [IEEE MTT-32, 829 (1984)], and Haslam, et al. [IEEE MTT-32, 829 (1984)]. The first two, by the French group (Mamouri, et al. and Bellarbi, et al.) report results of experiments at 3 GHz, but do not show actual measured data. The first paper does not even state the temperature of the source observed; the second gives a value of 15° C. The paper by Hill and Goldner gives sufficient data to evaluate the technique. Furthermore, actual measured results are given. They state that a 0.7° C source, wih an area of 325 mm^2, located 6.35 cm from the antennas in air, could be detected. The paper by Haslam et al. describes a hypothetical microwave imaging system based on aperture synthesis (a standard technique in radio astronomy). Evaluation of the signal to be expected for various idealized cases clearly show that signal strengths will be typically less than 0.2° C for most medical purposes. All the papers, cited above, seem to show that interferometry for microwave thermography will suffer from signal-to-noise problems.

In preparation for experiments related to correlation interferometry we have made bistatic measurements with one antenna driven by a noise tube or a signal generator, a second antenna attached to the reflection-compensating radiometer, and with a scattering object in the field-of-view of both antennas beneath layers of simulated tissue. The signal input to the radiometer is composed of the direct coupling between the two antennas plus the coherent signal scattered off the spherical (or cylindrical) object in the common field of view. As the antennas are scanned across the scattering object, only the component of the signal from the scatterer varies. In this manner we have found we can easily detect variations in dielectric constant at depths of 5 cm, or more. The resulting signal, because of the coherence, is the vector sum of the directly coupled electric field plus that from the scatterer. This technique may be of importance in the localization of tumors to be subjected to hyperthermia. The experimental set-up for our bistatic measurements is shown in Figure 4.

Bistatic scattering experiments represent an extension of microwave thermography which requires minor hardware additions but offers the potential of providing significant information about tumor size and the proper frequency for hyperthermia. Since tumors have different dielectric properties than the tissue medium in which they are imbedded their presence can be revealed by backscattering measurements. Furthermore, since the tumor will have a characteristic size the variation of the backscatter with frequency will provide information on their size since the radiation scattered in the backward direction will depend on the ratio of the characteristic size to the wavelength in the medium, λ_m. This can be shown most clearly by considering the scattering from dielectric spheres. If the radius of the sphere is r then the backscatter cross section varies as a r^4 when $r/\lambda_m < 0.1$. As r/λ_m increases, the cross section undergoes a series of resonances before approaching the value predicted by geometrical optics. The wavelengths at which the resonances occur can give a measure of the radius.

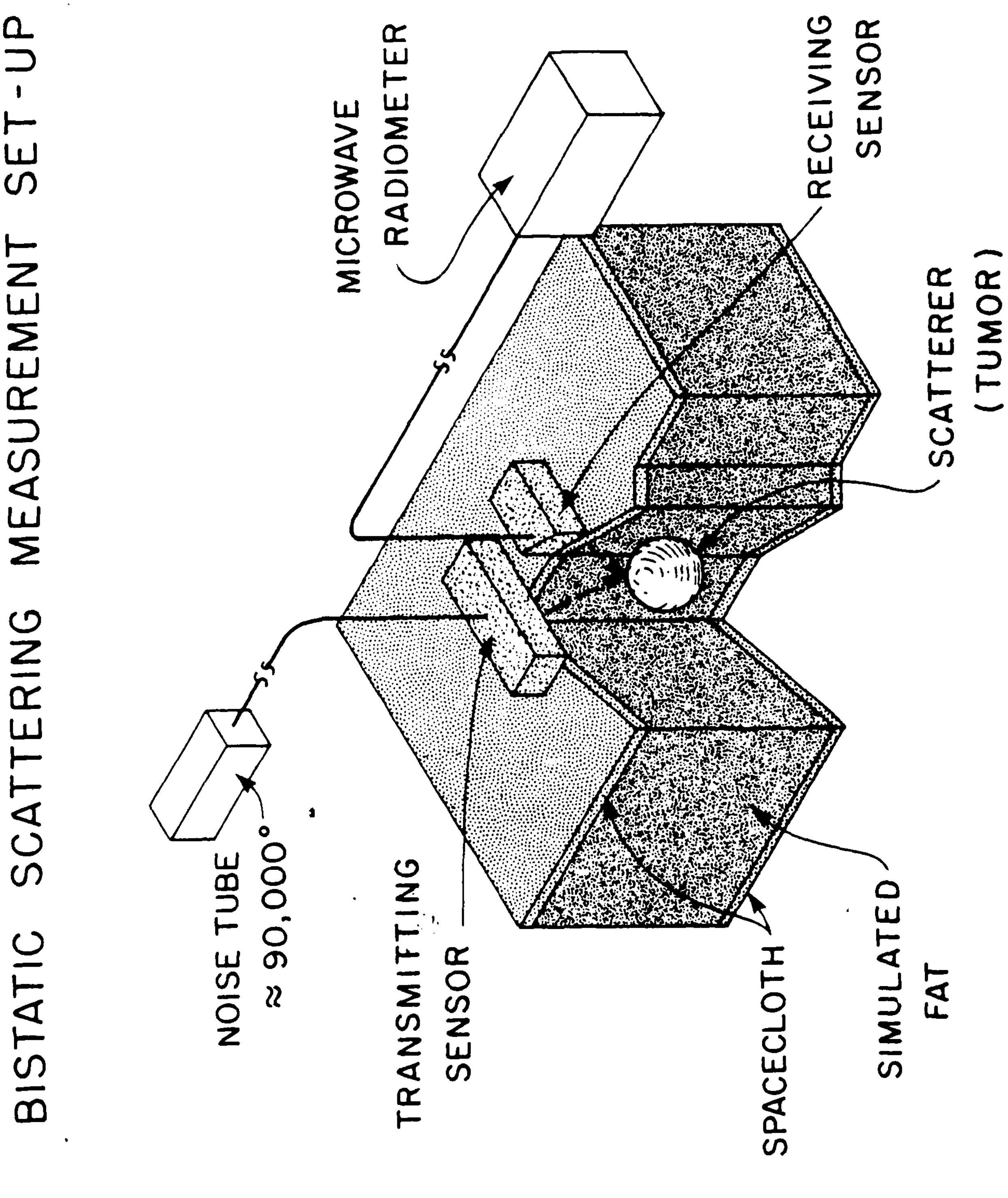
BISTATIC SCATTERING MEASUREMENT SET-UP
NOISE TUBE
≈ 90,000°
TRANSMITTING
SENSOR
SPACECLOTH
SIMULATED
FAT
MICROWAVE
RADIOMETER
RECEIVING
SENSOR
SCATTERER
(TUMOR)

Figure 4

The scattering from dielectric particles has been studied theoretically and experimentally since the work of Mie, Deby, and Rayleigh in the early 1900's. This work has assumed lossless particles, spherical shape, plane wave illumination of the particle, and observation of the scattered radiation in the far-field of the particle. None of these assumptions are applicable to our investigations. Nevertheless, our observations appear to show characteristic resonances in the scattering cross section which are related to d/λ_m, where d is a measure of the size of the scatterer.

If the difference in dielectric constant between a tumor and the surrounding regions is large then resonances can also occur in the absorption of elctromagnetic radiation by the tumor. This fact provides a means to optimize the frequency to be used for electromagnetic-induced hyperthermia. It may then be possible to heat the tumor specifically without a detrimental heating of the entire surrounding medium. Furthermore, by reciprocity, a resonance in absorption implies a resonance in emission, a fact which has not been exploited in microwave thermography.

Since the existence of a resonance depends on the ratio of d/λ_m, observations with a broadband device, such as a radiometer, necessarily averages over the bandwidth of the radiometer. If necessary this can be circumvented by replacing the noise tube by a signal generator and restricting the bandwidth of the radiometer with a tunable filter. We are experimenting with both approaches.

A summary of resonance phenomena in lossy dielectric spheres is given by Weil [IEEE Transactions on Biomedical Engineering, Vol. BME-22. No. 6, pp. 468-476, November 1975].

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